Body Mapping Of Sweating Patterns In Athletes: A Sex Comparison

By: **Caroline J. Smith** and George Havenith

Abstract

Purpose: Limited regional sweat rate (RSR) data are available for females, with only a small number of sites measured across the body. Similarly, sex differences in sweating concentrate on whole body values, with limited RSR data available. Methods: A modified absorbent technique was used to collect sweat at two exercise intensities (60% (I1) and 75% (I2) V˙ O2max) in 13 aerobically trained females (21 T 1 yr, 59.5 T 10 mLj1lminj1lkgj1 V˙ O2max) in moderately warm conditions (25-C, 45% relative humidity, 2 mlsj1 air velocity). Females were compared with nine aerobically trained males (23 T 3 yr, 70.2 T 13 mLj1lminj1lkgj1 V˙ O2max) tested under the same conditions. Results: Female I1 RSR was highest at the central upper back, heels, and dorsal foot and between the breasts (223, 161, 139, and 139 glmj2lhj1, respectively). Lowest values were over the breasts and the middle and lower outer back (G16 glmj2lhj1). At I2, the central upper back, bra triangle, and lower back showed the highest RSR (723, 470, and 333 glmj2lhj1, respectively). Regions of the breasts and palms had the lowest RSR at I2 (G82 glmj2lhj1). Significantly greater gross sweat loss and thus RSR were observed in males versus females at both exercise intensities. For the same metabolic heat production (male I1 vs female I2), absolute and normalized RSR showed a significant region–sex interaction (P G 0.001), with a greater distribution toward the arms and hands in females versus males. Conclusions: Despite some differences in distribution, both sexes showed highest RSR on the central upper back and the lowest toward the extremities. No correlation was observed between local skin temperature and RSR, failing to explain RSR variation observed. These data have important applications for sex-specific clothing design, thermophysiological modeling, and thermal manikin design.

Smith, C. & Havenith, G. (2012). Body Mapping of Sweating Patterns in Athletes: A Sex Comparison. Medicine & Science in Sports & Exercise, Volume 44(12), December 2012, p 2350-2361. DOI: 10.1249/MSS.0b013e318267b0c4. Publisher version of record available at: http://www.ovid.com/site/catalog/journals/586.jsp

Body Mapping of Sweating Patterns in Athletes: A Sex Comparison

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ABSTRACT

SMITH, C. J., and G. HAVENITH. Body Mapping of Sweating Patterns in Athletes: A Sex Comparison. *Med. Sci. Sports Exerc.*, Vol. 44, No.12, pp. 2350–2361, 2012. **Purpose**: Limited regional sweat rate (RSR) data are available for females, with only a small number of sites measured across the body. Similarly, sex differences in sweating concentrate on whole body values, with limited RSR data available. **Methods**: A modified absorbent technique was used to collect sweat at two exercise intensities (60% (I1) and 75% (I2) $\dot{V}O_{2max}$) in 13 aerobically trained females (21 ± 1 yr, 59.5 ± 10 $mL^{-1}{\cdot}min^{-1}{\cdot}kg^{-1}$ $\dot{V}O_{2max}$) in moderately warm conditions (25°C, 45% relative humidity, 2 $m{\cdot}s^{-1}$ air velocity). Females were compared with nine aerobically trained males (23 ± 3 yr, 70.2 ± 13 $mL^{-1}{\cdot}min^{-1}{\cdot}kg^{-1}$ $\dot{V}O_{2max}$) tested under the same conditions. **Results**: Female I1 RSR was highest at the central upper back, heels, and dorsal foot and between the breasts (223, 161, 139, and 139 $g{\cdot}m^{-2}{\cdot}h^{-1}$, respectively). Lowest values were over the breasts and the middle and lower outer back (<16 $g{\cdot}m^{-2}{\cdot}h^{-1}$). At I2, the central upper back, bra triangle, and lower back showed the highest RSR (723, 470, and 333 $g{\cdot}m^{-2}{\cdot}h^{-1}$, respectively). Regions of the breasts and palms had the lowest RSR at I2 (<82 $g{\cdot}m^{-2}{\cdot}h^{-1}$). Significantly greater gross sweat loss and thus RSR were observed in males versus females at both exercise intensities. For the same metabolic heat production (male I1 vs female I2), absolute and normalized RSR showed a significant region–sex interaction ($P <$ 0.001), with a greater distribution toward the arms and hands in females versus males. **Conclusions**: Despite some differences in distribution, both sexes showed highest RSR on the central upper back and the lowest toward the extremities. No correlation was observed between local skin temperature and RSR, failing to explain RSR variation observed. These data have important applications for sex-specific clothing design, thermophysiological modeling, and thermal manikin design. **Key Words:** SWEATING, METABOLIC RATE, SEX, SWEAT MAPPING, REGIONAL

The majority of thermoregulatory research available focuses on males rather than females and emphasizes core temperature and whole body sweat loss. Limited research is available on females, with a sparsity of information on regional sweat rates (RSR). Historically, RSR has been measured over a very limited number of sites or studies have used qualitative methods to assess sweating over large surface areas (28,29). More recently, several studies have measured RSR on multiple body regions (12,31–33,40,41,43); however, these studies used only males or reported combined data from both sexes. The only data currently available on females were limited to torso sweat rates (22), which identified significant regional variation between zones. The first study measuring RSR over almost the whole body surface area in males was recently published by Smith and Havenith (39), identifying both significant inter- and intraregional variation in sweating. To the knowledge of the authors, no study has attempted to measure RSR simultaneously over large skin surface areas for females.

Considerable debate surrounds sex differences in thermoregulation. Traditionally, women (testing a population average) are considered less effective in regulating body temperature than males in dry heat (37), with maintenance of a significantly lower sweat rate compared with men, and a substantially higher rectal temperature (7,13,14,37,38). A more pronounced delay in sweat onset has also been noted in women, attributed in part to a lower body water content (20) and potential effects of menstruation (25). Observations of sex-related differences in sweat rate, sweat thresholds (25), sweat gland size, and distribution (4,5,25) have contributed to the opinion that females generally sweat less than males. Conversely, several studies have observed that sex differences in thermoregulation cease to be significant upon matching subjects or correcting for anthropometric, acclimatization, and fitness parameters (2,3,14,15,23,24). Such disagreement in the literature must be viewed with careful consideration of the experimental design, measurement technique, and subject characteristics. Individual characteristics play a major role in thermoregulatory responses to heat stress (23,24) and are thought to explain a substantial part of response variation observed (17). More recently, however, studies supporting the existence of sex differences *per se* in thermoregulation have emerged; Madeira et al. (34) have demonstrated a greater pilocarpine-induced sweating responses in males compared

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with females when groups were matched for $\dot{V}O_{2peak}$. Aerobic capacity is known to enhance sudomotor response to pilocarpine in males (8), which may partially explain sex differences in local sweating in studies using unmatched groups. In addition, Gagnon and Kenny (19) observed lower evaporative heat loss and thermosensitivity in females despite a fixed absolute metabolic heat production and matching of physical characteristics between sexes.

This is of particular importance when considering fixed absolute versus relative work rates, whereby sex differences may be artificially created. During absolute work rate protocols, results may be confounded between groups if unmatched for $\dot{V}O_{2max}$ and/or body composition. Alternatively, when relative work rates are used, differences in absolute work rates and thus metabolic heat production may arise between sexes (18,21). Group "matching" is therefore important to consider, and in doing so, either comparing "average" individuals from each population or, to match $\dot{V}O_{2max}$, accepting that this is an unrepresentative sample from one population. With this in mind, the present study has taken an applied approach in comparing thermoregulatory responses between sexes in which the groups were selected for similar training and athletic performance levels (elite to subelite athletes) and were therefore not matched for physical characteristics. For exercise load, it was decided to use relative work rates that represent training and competition practice.

The aims of the present study were 1) to produce a whole body sweat map of aerobically trained females during mild exercise-induced hyperthermia and 2) compare these data to previously published body maps of sweating in aerobically trained males produced in our laboratory under the same experimental conditions (39). It was hypothesized that, similar to males, significant regional variation in sweat rate would be observed within the female group, with consistent patterns of variation between participants. It was further hypothesized that females would sweat significantly less than males because of a lower absolute metabolic heat production when exercising at a fixed relative workload, arising from a lower absolute aerobic capacity. Similar patterns of distribution of sweating were expected between sexes.

METHODS

Participants

Thirteen female unacclimated, aerobically trained, elite to subelite runners participated in whole body sweat mapping. All experimental procedures were approved by the Loughborough University Ethical Committee and were fully explained to the participants before obtaining informed written consent and completion of a healthscreen questionnaire.

Pretest Session

Participants attended the Environmental Ergonomics Research Center for anthropometric measurements of height, mass, and body dimensions used for the calculation of body surface area (9) and absorbent pad sizes. Skinfolds were taken using a four-point calliper method (26) specific to female athletes for calculation of body fat percentage. Aerobic fitness level, expressed as maximal oxygen uptake ($\dot{V}O_{2max}$), was calculated from a submaximal fitness test based on the Åstrand–Ryhming method (1). The test was conducted at an ambient temperature of 18°C to prevent thermal stress and composed of four exercise intensities running on a treadmill (h/p/cosmos mercury 4.0 h/p/cosmos sports & medical gmbh, Nussdorf-Traunstein, Germany) each lasting 5 min. Estimation of $\dot{V}O_{2max}$ was based upon the linear relationship between HR and work rate (work rate based upon treadmill speed and angle) (10).

Sweat pad preparation and application. RSR was determined using the method developed in our laboratory (12,22,39,40) by applying absorbent material directly to the skin for a short, predefined period (5 min). Two sets of absorbent pads were produced for each participant based on the anthropometric data (see online text, Supplemental Digital Content 1; http://links.lww.com/MSS/A171 for details of pad sizing). Pads were weighed (Sartorius YACOILA, Sartorius AG, Goettingen, Germany. Precision 0.01 g) inside individually labeled airtight bags, in which they were stored until testing. A total of 78 pads were used to produce a whole body sweat map for each exercise intensity (see Fig. 1 of online Supplemental Digital Content 2 (http://links.lww.com/MSS/A172) for sweat map pad locations). Pads were attached to custom-sized plastic sheeting for fast application to the body and to prevent the evaporation of sweat during the test periods. The pads were kept in place against the skin using a stretch long sleeve T-shirt and trousers. For the breast area, pads were attached inside a sports bra. On the feet, pads were secured in place on the ankles and dorsal surface of the foot inside 100% cotton socks, which were also used to collect sweat from the top of the foot. Plastic stretch socks were worn on top to prevent evaporation of sweat from the cotton socks during the measurement period. Similarly, 100% cotton gloves were worn to collect sweat on the hands, with small incisions made at the base of each finger to prevent the migration of sweat between regions, while maintaining their structural integrity during the test. Latex gloves were worn over the cotton gloves during the measurement period to secure the gloves in place against the skin and prevent sweat evaporation.

Experimental Protocol

Experimental sessions were conducted in a climate-controlled room at 25.7°C ± 0.4°C, 45% ± 7% relative humidity, and a 2 $m \cdot s^{-1}$ frontal air velocity. Data were obtained in three identical experimental sessions per participant, with approximately one third of the skin surface area covered in each test, thus allowing enough exposed skin for thermoregulation. The three sessions focused on 1) torso/upper body (UB), 2) legs, and 3) arms, hands, buttocks, and feet (AHBF). Testing sequence was balanced to prevent any order effect and performed at the same time of day to minimize circadian variation. Menstrual cycle phase was not controlled for during

experimental sessions; participants were tested over a wide range of the menstrual cycle, providing a representative sample of menses state in the results.

On arrival to the laboratory, participants were provided with shorts and T-shirt and then weighed. Infrared images (Thermacam B2; FLIR Systems Ltd., West Malling, Kent, UK) of the nude, dried skin were taken before testing, before and after each pad application, and immediately after testing to monitor skin temperature (Tsk). Resting HR was recorded before participants warmed up, with HR monitored throughout the experiment at 15-s intervals. T_{core} was measured using a VitalSense Integrated Physiological Monitoring System (Mini Mitter Company, Inc., Bend, OR). Participants swallowed a CorTemp™ ingestible temperature pill 5 h before testing. Throughout the experiment, the VitalSense monitor wirelessly tracked and recorded T_{core} four times per minute. Participants ran for a total of 60 min involving two exercise intensities of 30 min each on the treadmill with an incline of 1%. The target HR was 125–135 and 150–160 bpm for intensity 1 (I1) and intensity 2 (I2), respectively, to control workload at the targets of 60% and 75% of $\dot{V}O_{2max}$. Exercise intensities were not separated by a break; however, subjects were required to step off the treadmill for all measurements and pad application/removal (approximately 3 min). Participants removed their clothing and toweled their skin dry immediately before pad application to ensure only sweat produced during the sample period was collected. All of the pads had an impermeable backing to prevent evaporation. Sweat samples were taken during the last 5 min of each exercise intensity at 30 and 60 min, during which time the participants returned to the treadmill donning the absorbent pads. Immediately after the sample periods, the pads were quickly returned to their airtight bags and sealed. The participants could drink water freely during the experiment, which was recorded, to prevent dehydration. After the 60-min run, final measurements of core temperature, skin temperature, and body weight were recorded. All pads were reweighed inside their sealed bags. The cotton glove and sock segments could not be individually weighed before testing because they were not yet separated from each other. Immediately after sweat collection, specific sections of the gloves and socks were dissected and placed in individually labeled airtight bags. The posttest wet weight of each sample was recorded before being dried out in a thermal chamber at 30°C, 50% relative humidity, for 24 h then reweighed to obtain the "dry" (pretest) weight. The surface area of each pad was calculated from the dry weight of each pad and the weight per unit of surface area of the material. Local sweat rate was calculated in grams per meter square of body surface area per hour ($g \cdot m^{-2} \cdot h^{-1}$) using the weight change of the pad, the pad surface area, and duration of application to the skin.

Analysis

Because data from the different experimental sessions were to be combined in a whole body sweat map, and because sweat rates may differ, even between identical sessions for an individual, it was decided to correct individual session data in line with the session's gross sweat loss (GSL) value. Data for each individual were standardized toward the mean GSL over all three sessions for that individual. All corrections work on the assumption that within each workload, there is a relation between regional and GSL for an individual.

GSL was calculated based on the weight change of each participant across each test period, adjusted for fluid intake. Corrections were made for respiratory and metabolic mass losses. Evaporative loss from respiration (E_{res} (W)) was calculated using equation 1, based upon the work described by Livingstone et al. (30):

$$E_{res} = 1.27 \times 10^{-3} M(59.34 + 0.53T_a - 11.69P_a) \quad [1]$$

and converted into mass loss (g):

$$\text{mass loss} = E_{res} t \frac{1}{2430} \quad [2]$$

where E_{res} is the evaporative loss from respiration (W); M, metabolic rate (W); T_a, air temperature (°C); t, time: duration of intensity or experiment (s); and 2430, latent heat of evaporation of 1 g of water ($J \cdot g^{-1}$).

Metabolic mass loss (g) was calculated based upon Kerslake (27):

$$\text{metabolic mass loss} = \left(\frac{\dot{V}O_2(44RQ - 32)}{22.4}\right) t \quad [3]$$

where $\dot{V}O_2$ is rate of oxygen consumption ($L \cdot min^{-1}$); RQ, respiratory quotient (ND); t, time (s).

The RQ was taken as 0.85 for intensity 1 and 1.00 for intensity 2 (35).

Sweating sensitivity for each segment (i) was calculated as follows:

$$\text{gain}_{1,i} = \frac{\text{sweat rate increase intensity 1}}{\text{core temperature increase intensity 1}} \quad [4]$$

$$\text{gain}_{2,i} = \frac{\text{sweat rate intensity 2} - \text{sweat rate intensity 1}}{\text{core temperature increase intensity 2}} \quad [5]$$

Finally, overall sweat sensitivity was calculated for comparison with literature (31–33,43) as follows:

$$\text{overall gain}_i = \frac{\text{sweat rate increase over experiment}}{\text{core temperature increase over experiment}} \quad [6]$$

Paired sample t-tests were performed both with and without Bonferroni correction to analyze right–left differences in sweat rate and changes with exercise intensity. A one-way repeated-measures ANOVA was performed to analyze regional differences within each intensity, presented both with and without Bonferroni correction for *post hoc* comparisons. Both values are presented first because of the exploratory nature of the study and second because of the large number of zones studied compared with any earlier study (6,36). This makes the Bonferroni correction very stringent, and zones that would show significance in a smaller study will struggle to reach significance here. For RSR comparison between sexes, a two-way repeated-measures ANOVA was performed with sex

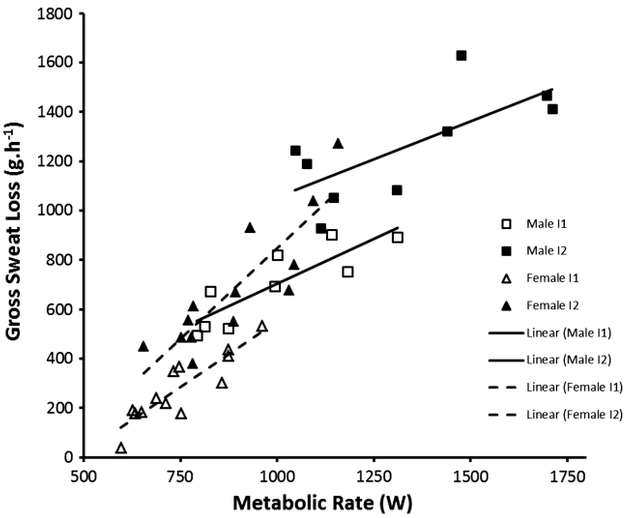

FIGURE 1—Absolute mean GSL ($g \cdot h^{-1}$) and absolute mean metabolic rate (W) for trained females and males at exercise intensity 1 (I1) and intensity 2 (I2). Male data have been modified from Smith and Havenith (39).

(between-subject factor), region, and sex–region interaction as factors. To allow direct comparison of the upper chest between sexes despite the use of differing pads, the upper chest (three pads) in the males and the upper chest and bra pads (11 pads) in the females were area weighted to produce a single "upper chest" sweat rate value for each sex.

To allow standardization of sweat data over participants and for the easy identification of "higher" and "lower than average" sweat regions regardless of absolute sweat rates, RSR was normalized for the area-weighted sweat rate of all zones. The same analysis was performed on the normalized regional sweat data as described above for the absolute data. Pearson correlation coefficient was calculated to assess correlations between RSR and regional T_{sk} and RSR and GSL. Finally, it was decided that it would be more relevant to graphically show results for the "average sweater" (the median) rather than the "average amount of sweat produced" (the mean) because the latter can be affected more easily by outliers, i.e., extreme sweaters. In tables, both values are presented to provide insight into the data distribution.

Male data presented in the present article have been reported previously (39) and are in part included here to allow comparison with the female data.

RESULTS

Participant Characteristics

Female subjects were significantly shorter (female, 165 ± 8 cm, vs male, 179 ± 4 cm, $P < 0.001$), were lighter (59 ± 7 vs 74 ± 5 kg, $P < 0.001$), had a smaller surface area (1.64 ± 0.10 vs 1.92 ± 0.10 m^2, $P < 0.001$), and showed a higher body fat percentage than males (18% ± 4% vs 11% ± 5%, $P < 0.01$). Although age was significantly different between groups (female, 21 ± 1 yr, vs male, 23 ± 3 yr, $P = 0.047$), this was not biologically relevant. Females had a significantly lower $\dot{V}O_{2max}$ (59.5 ± 10 vs 70.2 ± 13 $mL \cdot kg^{-1} \cdot min^{-1}$, $P < 0.05$) with a value 85% that of the trained males. When based on fat-free mass, females had a $\dot{V}O_{2max}$ 92% that of males (female, 78.9 $mL \cdot kg^{-1} \cdot min^{-1}$, vs male, 72.6 $mL \cdot kg^{-1} \cdot min^{-1}$).

Core Temperature, Work Rate, and HR

Female data. Baseline data (BL) were taken as the temperature and HR recorded immediately before commencing I1. Reported I1 and I2 data were the mean values over the final 5 min of each intensity. T_{core} increased significantly from 37.29°C ± 0.29°C at baseline to 37.83°C ± 0.19°C at I1 (BL to I1 ΔT_{core} = 0.54°C ± 0.21°C, $P < 0.001$) and to 38.06°C ± 0.24°C at I2 (ΔT_{core}; BL to I2 = 0.77°C ± 0.35°C, $P < 0.001$, I1 to I2 = 0.23°C ± 0.25°C, $P < 0.01$). HR increased significantly from 66 ± 13 bpm at baseline to 134 ± 3 at I1 ($P < 0.001$) and to 157 ± 3 ($P < 0.001$) at I2, reflecting relative work rates of 61% ± 7% and 72% ± 11% $\dot{V}O_{2max}$ for I1 and I2, respectively.

Sex comparison. No differences in HR were present between groups for either exercise intensity; however, running speed ($km \cdot h^{-1}$) was significantly higher in males compared with females (I1, 10.4 ± 2.0 vs 8.5 ± 1.7, $P < 0.05$; I2, 13.6 ± 2.2 vs 10.5 ± 1.7, $P < 0.01$). Males showed a lower resting T_{core} than females (male, 36.93°C ± 0.39°C, $P < 0.05$), but no sex difference was present at the end of either exercise intensity (male I1 = 37.68°C ± 0.45°C, I2 = 38.06°C ± 0.44°C). ΔT_{core} was significant over both exercise intensities (male ΔT_{core}; BL to I1 = 0.76°C ± 0.18°C, I1 to I2 = 0.45°C ± 0.30°C, $P < 0.001$) in both sexes, with the rise being significantly greater in males from BL to I1, reflecting the lower resting T_{core} ($P < 0.05$).

GSL

Female data. Substantial variation in GSL was observed both within (between sessions) and between participants. The mean GSL of all sweat mapping experiments was 272 ± 103 $g \cdot m^{-2} \cdot h^{-1}$, with mean values for UB/torso, legs, and AHBF sessions of 300 ± 113, 268 ± 95, and 246 ± 101 $g \cdot m^{-2} \cdot h^{-1}$, respectively. The mean surface areas covered in each experiment were 0.49, 0.45, and 0.33 m^2 for the AHBF, legs, and UB experiments, respectively, totaling 1.28 m^2. The percentage of body coverage was 30.1%, 27.7%, and 20.2% over the three experiments, totaling 78% of the whole body. GSL increased significantly with exercise intensity ($P < 0.001$) from 168 ± 81 to 410 ± 144 $g \cdot m^{-2} \cdot h^{-1}$ and correlated positively with $\dot{V}O_{2max}$ ($r = 0.71$, $P < 0.01$), and for individual work intensities (Fig. 1), GSL ($g \cdot h^{-1}$) correlated positively with metabolic rate (W; I1 $r = 0.89$, $P < 0.001$; I2 $r = 0.87$, $P < 0.05$) with no significant difference present between the gradient of regression lines for each exercise intensity.

Sex comparison. Males showed significantly higher GSL compared with females both during each exercise

TABLE 1. Descriptive statistics for all regions sampled at I1 and I2 for female subjects.

			Absolute Sweat Data ($g \cdot m^{-2} \cdot h^{-1}$)										Normalized Ratio Data				Pearson *r*		Significance Level of Intensity Comparison		Sudomotor Sensitivity		
			I1					I2					I1		I2		GSL and RSR				($g \cdot m^{-2} h^{-2} \cdot °C^{-1}$)		($mg \cdot cm^{-2} \cdot min^{-1} \cdot °C^{-1}$)
	n	Surface Area (m^2)	Min	Max	Median	Mean	SD	Min	Max	Median	Mean	SD	Median	IQR	Median	IQR	I1	I2	Absolute Data	Normalized Ratio Data	I1	I2	Overall
Shoulders	13	0.052	3	240	40	80	83	65	570	138	189	130	0.72	0.78	0.94	0.39	0.92	0.72	***,##	***,#	78	426	0.42
Upper chest	13	0.023	0	300	58	64	80	44	478	199	185	131	0.38	0.64	0.88	0.51	0.52	0.66	***,#	***,#	112	613	0.41
Medial upper bra	13	0.009	0	93	22	34	39	0	402	145	153	142	0.27	0.46	0.70	1.23	0.60	0.60	**	*	43	535	0.34
Lateral upper bra	13	0.010	0	86	0	18	29	0	180	46	72	72	0.00	0.18	0.34	0.44	0.79	0.81	**,$	**,$	0	202	0.16
Medial lower bra	13	0.009	0	184	0	27	52	0	361	57	92	112	0.00	0.35	0.27	0.52	0.53	0.61	*	–	0	248	0.21
Lateral lower bra	13	0.010	0	48	0	5	13	0	76	0	16	26	0.00	0.00	0.00	0.09	0.65	0.67	–	–	0	0	0.03
Bra triangle	13	0.002	0	2251	139	418	664	0	3940	723	912	1038	1.19	6.85	4.85	7.01	0.39	0.51	**,$	–	270	2539	2.04
Lateral middle chest	13	0.032	0	210	31	55	63	16	221	83	109	68	0.36	0.50	0.51	0.39	0.79	0.64	***,#	–	60	225	0.24
Medial middle chest	13	0.016	0	159	57	67	57	31	253	97	130	75	0.62	0.53	0.70	0.37	0.72	0.50	***,##	–	110	174	0.29
Sides	13	0.034	23	322	67	96	88	81	350	211	192	86	0.71	0.57	0.93	0.62	0.71	0.45	***,#	–	130	626	0.43
Anterior lower	13	0.016	0	292	49	73	83	12	384	106	144	105	0.52	0.48	0.70	0.78	0.59	0.31	***,#	–	95	248	0.32
Lateral upper back	13	0.035	7	399	138	162	130	119	601	324	338	151	1.44	0.64	1.86	0.40	0.89	0.76	***,###	–	268	807	0.76
Medial upper back	13	0.019	21	814	223	282	227	141	963	470	496	228	2.29	1.37	2.86	1.16	0.80	0.69	***,##	–	433	1076	1.11
Lateral middle upper back	13	0.017	0	284	13	80	105	0	413	137	186	137	0.18	1.09	0.92	0.42	0.68	0.77	**	–	25	538	0.42
Lateral middle lower back	13	0.017	0	273	16	66	88	30	337	83	129	114	0.33	0.67	0.66	0.60	0.83	0.67	**,$	–	31	292	0.29
Medial middle back	13	0.017	0	473	133	166	146	45	613	304	340	162	1.53	1.06	1.94	0.48	0.88	0.85	***,###	*	258	743	0.76
Posterior lower back	13	0.015	0	466	132	164	168	14	598	333	300	190	1.36	2.26	1.83	1.13	0.79	0.55	**,$	–	257	875	0.67
Anterior upper leg	12	0.065	32	275	111	123	71	44	451	160	190	117	1.20	0.47	0.97	0.40	0.89	0.84	**,$	–	215	214	0.42
Medial upper leg	12	0.065	28	276	71	101	73	47	351	138	152	89	1.00	0.18	0.82	0.15	0.82	0.87	**,$	–	137	293	0.34
Posterior upper leg	12	0.065	41	221	88	100	54	67	293	114	144	84	0.97	0.34	0.75	0.32	0.77	0.72	**	–	171	112	0.32
Lateral upper leg	12	0.065	57	205	111	118	49	53	366	123	166	106	1.28	0.35	0.91	0.40	0.72	0.70	*	*	216	51	0.37
Anterior lateral lower leg	13	0.049	19	364	75	122	98	24	372	140	164	109	1.12	0.74	0.90	0.65	0.78	0.73	**	–	145	285	0.37
Anterior medial lower leg	13	0.049	31	308	99	132	85	30	448	159	197	127	1.39	0.31	1.23	0.40	0.78	0.73	**,$	–	193	260	0.44
Posterior lower leg	13	0.095	42	218	81	102	57	57	295	112	141	77	0.99	0.45	0.74	0.30	0.77	0.72	**,$	*	158	134	0.32
Anterior upper arm	13	0.060	0	172	67	80	61	58	282	133	145	72	0.76	0.24	0.83	0.17	0.93	0.91	***,##	–	131	287	0.33
Posterior upper arm	13	0.060	0	177	52	68	67	19	272	138	139	74	0.55	0.57	0.78	0.29	0.89	0.78	***,##	*	101	374	0.31
Anterior lower arm	13	0.053	0	293	68	101	96	51	427	185	188	106	0.86	0.86	1.09	0.20	0.87	0.87	***,##	*	131	511	0.42
Posterior lower arm	13	0.052	0	275	89	104	98	12	393	257	209	123	0.97	0.98	1.22	0.43	0.91	0.71	**,$	–	173	729	0.47
Thumbs	13	0.010	16	233	104	118	80	56	503	142	195	119	1.16	1.01	1.08	0.40	0.59	0.39	*	–	203	161	0.44
Fingers	13	0.039	13	135	70	70	40	23	148	113	103	37	0.68	0.61	0.69	0.34	0.47	0.27	**,$	–	136	185	0.23
Palms	13	0.030	1	152	43	58	44	15	153	82	80	32	0.62	0.32	0.55	0.18	0.56	0.31	*	–	83	168	0.18
Back hand	13	0.033	9	315	106	118	96	34	308	151	163	90	1.02	1.03	1.07	0.45	0.53	0.64	*	–	205	199	0.37
Buttocks	13	0.037	15	267	120	110	68	62	325	192	190	74	1.07	0.71	1.17	0.33	0.56	0.23	**,$	–	233	314	0.43
Sole	13	0.017	59	160	116	119	33	56	154	125	119	33	1.40	1.66	0.89	0.58	0.09	−0.20	–	**,$	225	40	0.27
Dorsal foot	13	0.056	32	157	139	115	46	34	195	131	124	49	1.32	0.77	0.81	0.57	0.28	0.13	–	**,$	269	−31	0.28
Toes	13	0.010	81	219	114	130	41	29	213	108	121	52	1.66	1.84	0.91	0.88	−0.33	−0.52	–	**,$	222	−28	0.27
Heel	13	0.007	69	233	161	148	52	46	209	131	129	45	1.43	1.95	0.92	0.67	−0.34	−0.33	–	**,$	313	−132	0.29
Medial ankle	13	0.015	16	368	101	144	130	21	332	192	196	95	1.10	1.18	1.17	0.92	0.71	0.02	–	–	197	392	0.44
Lateral ankle	13	0.014	0	284	47	91	92	0	260	128	127	68	0.73	0.64	0.85	0.63	0.65	−0.04	–	–	91	353	0.28

Statistical comparison of sweat rates within each region between exercise intensities for both absolute and normalized data, corrected and uncorrected for multiple comparisons.

n = number of participants. Gray shading in columns for normalized ratio data indicates significant deviation from 1, i.e., average sweat rate. A decrease in median sweat rate ratio between intensities is indicated by black shading in the intensity comparison column. Sudomotor sensitivity for all regions tested, calculated as changes in RSR divided by change in T_{core} (ΔT_{core}), for both intensities and overall (43). For conversion of absolute sweat rates (in $g \cdot m^{-2} \cdot h^{-1}$) to other units, divide by 600 to get $mg \cdot cm^{-2} \cdot min^{-1}$ or by 10,000 to get $mg \cdot cm^{-2} \cdot h^{-1}$.

Level of significance with no correction for multiple comparisons: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

Level of significance following Bonferroni correction: # $P < 0.05$, ## $P < 0.01$, ### $P < 0.001$, \$0.05 < $P < 0.1$.

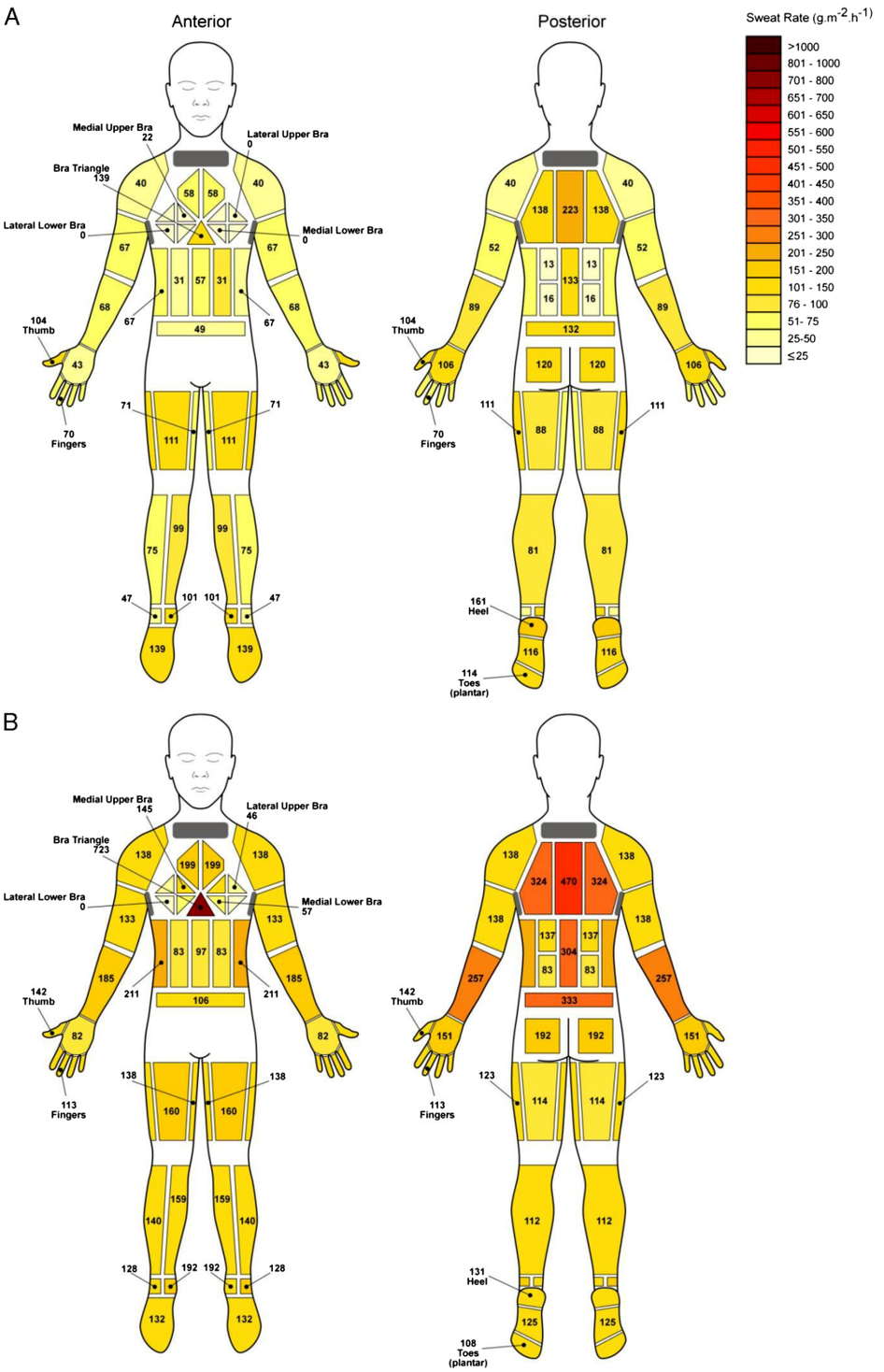

FIGURE 2—Absolute regional median sweat rates of female athletes at exercise intensity 1 (panel A) and exercise intensity 2 (panel B). The sweat rate scale is the same as that used for male absolute sweat maps from Smith and Havenith (39) to allow direct comparison between data sets.

intensity and overall (male GSL: I1, 364 ± 84 $g \cdot m^{-2} \cdot h^{-1}$; I2, 657 ± 119 $g \cdot m^{-2} \cdot h^{-1}$; overall, 458 ± 115 $g \cdot m^{-2} \cdot h^{-1}$; male vs female GSL all $P < 0.001$). When GSL was plotted against $\dot{V}O_{2max}$, no significant differences between the gradient of the regression lines or the intercepts were present between sexes. Metabolic heat production was significantly greater in males than females expressed in absolute terms (Fig. 1: male I1, 993 ± 185 W; I2, 1335 ± 259 W;

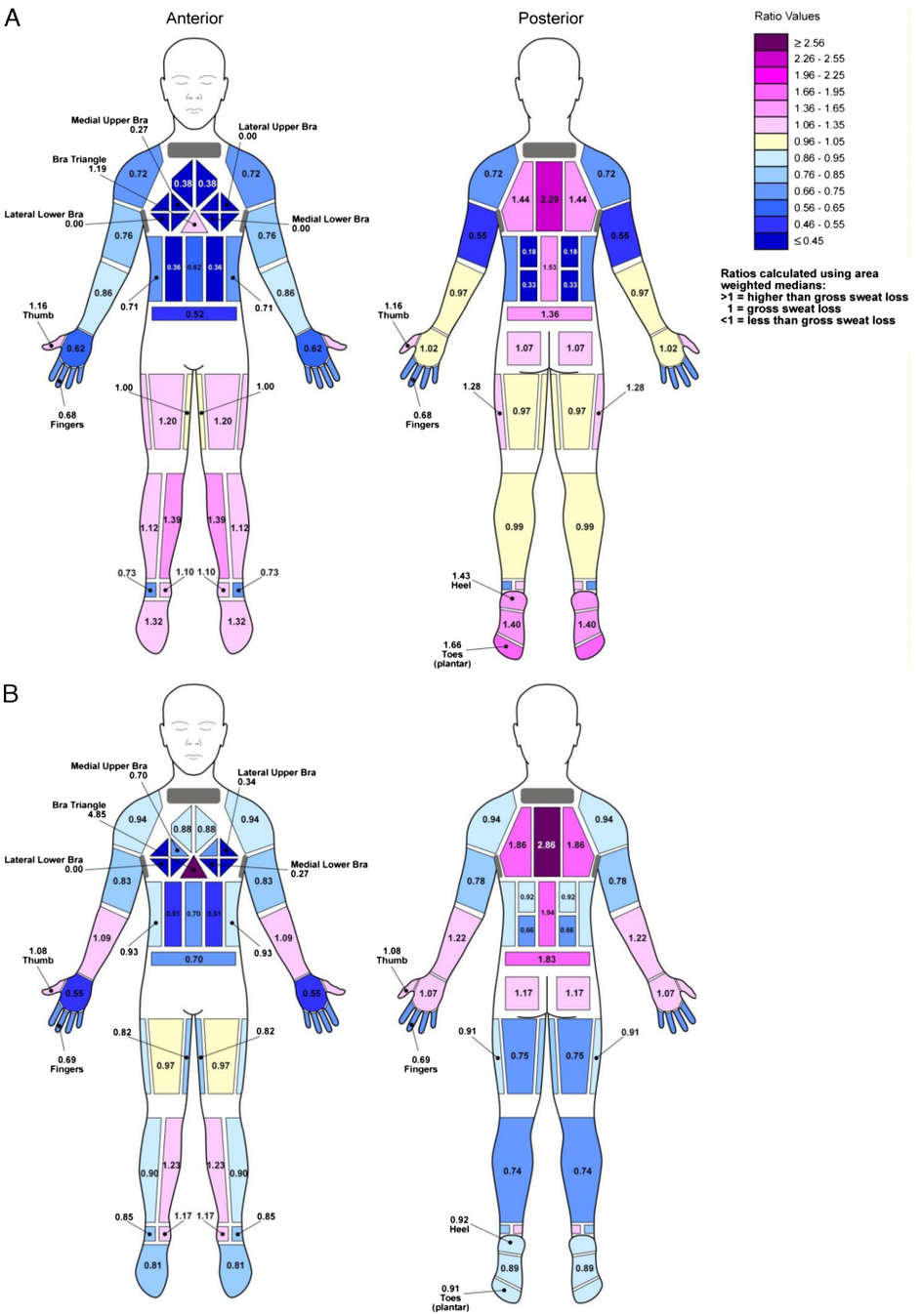

FIGURE 3—Normalized regional median sweat rates of female athletes at exercise intensity 1 (panel A) and exercise intensity 2 (panel B).

both $P < 0.001$), but only at I2 when expressed as a function of surface area (male I1, 519 ± 103 $W \cdot m^{-2}$, $P = 0.081$; I2, 697 ± 137 $W \cdot m^{-2}$, $P < 0.01$).

RSR

Female data. RSR data were grouped for corresponding right and left zones because only one zone showed a bilateral difference. Median grouped data for all participants are illustrated for both exercise intensities in Figure 2. The pads illustrated in gray, located below the anterior and posterior neck and at the axilla, acted to absorb excess sweat, which might otherwise have dripped from these areas and thus preventing it from being absorbed by adjacent pads. These extra pads were discarded after sweat collection and were not used in sweat mapping calculations. The highest sweat rates observed at I1 were at the central upper back, heels, and dorsal foot and between the breasts, with values of 223, 161, 139, and 139 $g \cdot m^{-2} \cdot h^{-1}$, respectively. Sweat rate increased at all regions with increasing exercise intensity, with exception of the feet, ankles, and the lateral lower breast (Table 1). At I2,

TABLE 2. Comparison of male and female absolute ($g \cdot m^{-2} \cdot h^{-1}$) and ratio regional sweat data for exercise intensity 1 (I1) and 2 (I2).

	Absolute Sweat Data ($g \cdot m^{-2} \cdot h^{-1}$)		Normalized Ratio Data		Male I1 and Female I2 Sweat Data Comparison	
	I1	I2	I1	I2	Normalized Ratio Data	Ratio Data
Shoulders	***,###	***,##	**	**	*	–
Upper chest	***,###	***,###	**,$	*	*	–
Lateral middle chest	***,###	***,##	**,$	*	***,##	–
Medial middle chest	***,###	***,##	**,$	**	***,##	*
Sides	**	**	–	–	–	–
Anterior lower	**	***,##	–	–	–	–
Lateral upper back	***,###	***,###	*	–	**	–
Medial upper back	***,#	***,##	–	–	*	–
Lateral middle upper back	***,###	***,###	**	*	**	–
Lateral middle lower back	***,###	***,##	***,##	***,##	**,$	**,$
Medial middle back	***,###	***,##	**,$	*	***,##	*
Posterior lower back	***,##	***,#	*	–	**	–
Anterior upper leg	**,$	**,$	–	–	–	–
Medial upper leg	*	*	–	–	–	–
Posterior upper leg	***,#	**	–	–	–	–
Lateral upper leg	**	**,$	–	–	*	*
Anterior lateral lower leg	*	**	–	–	*	–
Anterior medial lower leg	**	***,#	–	–	*	–
Posterior lower leg	***,##	***,##	–	–	**	–
Anterior upper arm	*	**	–	**	–	***,##
Posterior upper arm	–	**	–	–	–	*
Anterior lower arm	*	**,$	–	–	–	*
Posterior lower arm	*	**	–	–	–	–
Thumbs	–	–	*	**,$	–	**
Fingers	–	*	*	**	–	*
Palms	–	*	*	*	–	–
Back hand	–	–	–	*	–	**
Buttocks	**	**,$	–	–	–	–
Sole	*	**	**	–	**	–
Top foot	*	**	–	–	**	–
Toes	–	*	**	*	–	–
Heel	–	*	**,$	*	–	–
Medial ankle	*	**	–	–	*	–
Lateral ankle	*	**	–	–	–	–

A comparison of male exercise intensity 1 and female intensity 2 absolute and ratio regional sweat data are presented in the far right hand columns.
Level of significance for male versus female comparisons with no correction for multiple comparisons: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.
Level of significance following Bonferroni correction: # $P < 0.05$, ## $P < 0.01$, ### $P < 0.001$, \$0.05 < $P < 0.1$.

the central upper back and the area between the breasts showed the highest sweat rates with values of 723 and 470 $g \cdot m^{-2} \cdot h^{-1}$ compared with significantly lower values on the breasts and toward the extremities. Detailed comparisons of all absolute RSR within each exercise intensity may be viewed in the Supplemental Digital Content 3 (http://links.lww.com/MSS/A173) (Tables 1–4). "Higher" and "lower than average" sweat rates may easily be identified using normalized RSR data, illustrated in Figure 3. Regions with sweat rate ratios significantly different from average (=1) are denoted in Table 1 by gray shading in the ratio column. A comparison of normalized ratio data between exercise intensities indicated little change in distribution between I1 and I2, with exception to a significant decrease in distribution toward the feet and shoulders and an increase toward the breasts at the higher exercise intensity.

Sex comparison. Regional absolute and normalized sweat data for male athletes (adapted from Smith and Havenith [39]) are presented in Figure 4. Absolute and normalized data comparisons between sexes are presented both with and without Bonferroni correction in Table 2. As expected, males showed significantly greater absolute local sweat rates compared with females at both exercise intensities, with exception of areas of the hands and feet at I1 and only the thumbs and dorsal hand at I2. Both sexes did exhibit similarities in RSR, showing 1) greater sweat rates on the anterior compared with the posterior torso, 2) a medial to lateral decrease in sweat rates across the torso, 3) the greatest sweat rates on the central and lower back (with exception to the bra triangle in females at I2), and 4) the lowest sweat rates toward the extremities. Normalized ratio data (Fig. 3. vs Fig. 4B) indicated a significantly higher distribution of sweat toward the torso in males, and females showing a significantly higher distribution toward the hands and feet compared with males at both exercise intensities.

Because no significant difference in absolute metabolic rate was present between sexes for male I1 compared with female I2, a comparison of absolute and normalized data between sexes was performed for these data (Table 2). GSL did not differ significantly between males at I1 compared with females I2 when compared in absolute terms (male, 699 ± 157 $g \cdot h^{-1}$, vs female, 685 ± 260 $g \cdot h^{-1}$, $P = 0.887$), nor when normalized for body surface area (365 ± 84 vs 410 ± 131 $g \cdot m^{-2} \cdot h^{-1}$, $P = 0.379$). Absolute RSR remained significantly higher in males compared with females on the torso, legs, and areas of the feet, representing 17 of the 34 regions compared.

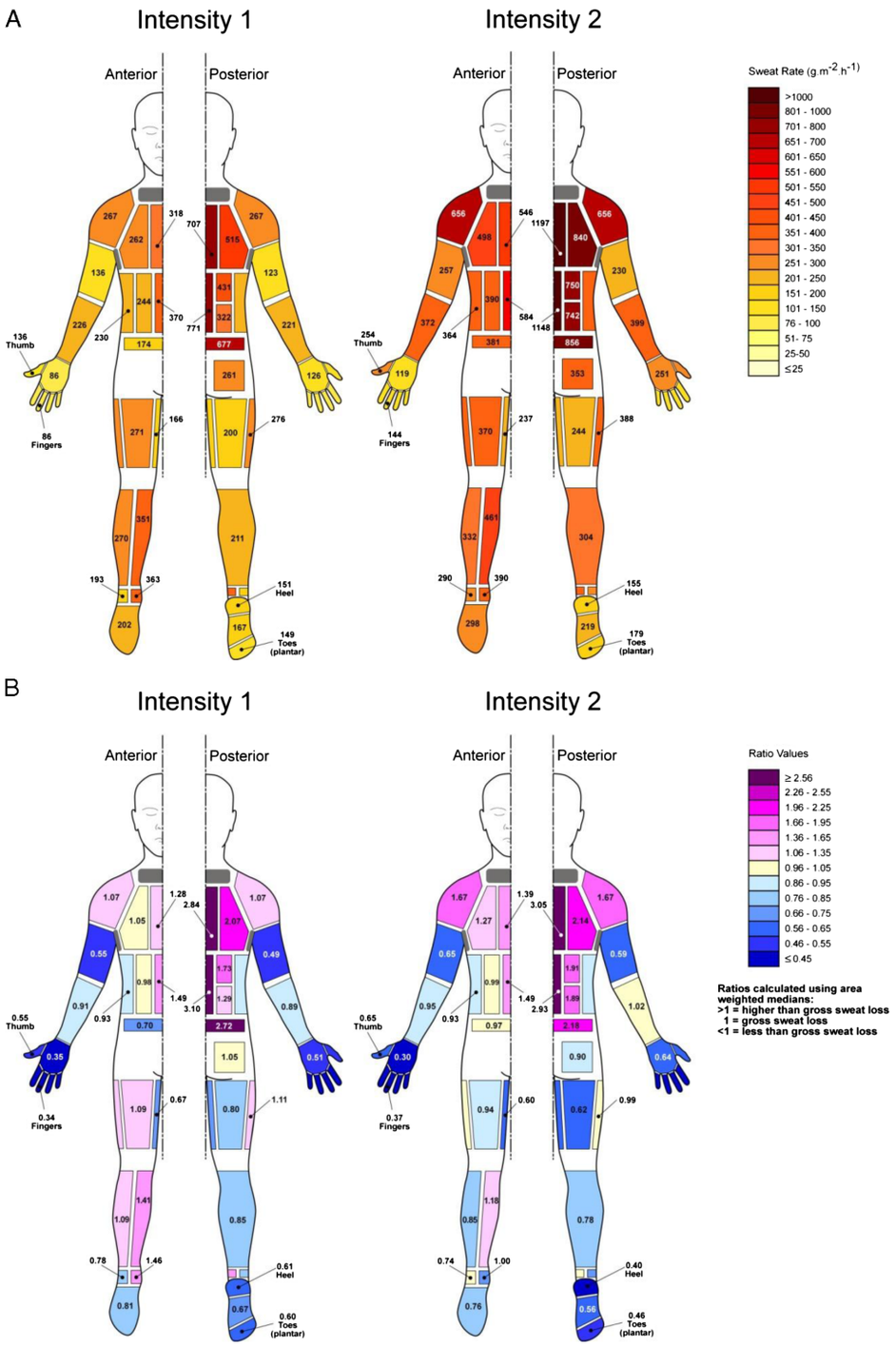

FIGURE 4—Absolute (panel A) and normalized (panel B) regional median sweat rates of male athletes at exercise intensity 1 and 2. These data have been adapted from Smith and Havenith (39) for direct comparison with the female data.

Despite significantly greater sweat rates in males, regions of high and low sweating were similar between sexes. A significant region–sex interaction for both I1 and I2 normalized data ($P < 0.001$) did however indicate some differences in distribution. Fewer differences were present in relative sweat distribution compared with absolute data, with the main exception being significantly greater ratio values for the arms and hands in females compared with males, with significance present at 9 of the 34 regions compared.

Skin Temperature

Female data. Regional T_{sk} data were right and left grouped because only 5 of the 48 regions measured showed

significant bilateral differences, and no significant differences after Bonferroni correction. T_{sk} increased from baseline to I1 at only the feet and ankles (uncorrected: heels, soles, and dorsal foot, $P < 0.001$, ankles, $P < 0.05$; corrected: heels and soles, $P < 0.001$, dorsal foot, $P < 0.01$), reflecting their low baseline temperatures. The lowest baseline T_{sk} of 26.5°C was observed at the heels compared with the highest value of 34.0°C at the anterior upper chest and medial upper back. Interestingly, the mean increase in T_{sk} of all regions from pre- to postpad application was 1.1°C for both I1 and I2, reflecting the effect of the measurement technique itself on T_{sk}.

A within-participant analysis of the correlation between RSR and corresponding regional T_{sk} was performed to avoid the potentially confounding effects of between-participant factors on T_{sk} and RSR (particularly absolute work rate affecting SR). RSR and regional T_{sk} were not correlated in any participant at either exercise intensity or across measurement periods (mean ± SD Pearson r correlation: I1, 0.14 ± 0.34; I2, 0.06 ± 0.17).

Sex comparison. No significant differences in regional T_{sk} were present between sexes at any measurement period with exception to baseline. Similar to the females, the lowest regional T_{sk} for males at baseline of 25.8°C was at the heels, compared with the highest of 32.5°C observed on the anterior upper arm. T_{sk} at baseline was significantly higher in females at all regions of the UB (torso: posterior medial upper, posterior lateral upper, $P < 0.05$; anterior upper, anterior medial lower, anterior lateral lower, posterior medial lower, posterior lateral lower, $P < 0.01$; sides, $P < 0.001$). The posterior medial upper, posterior lateral upper, anterior medial lower, and posterior lateral lower regions did not show significance after Bonferroni correction. Absolute regional T_{sk} increased significantly at only the feet and ankles during I1, with most sites on the torso and the anterior arms increasing from I1 to I2. The mean increase in T_{sk} over all regions during pad application was 0.9°C during I1 and 0.8°C during I2, reflecting the effect of the procedure on T_{sk} (for complete regional T_{sk} data, see Supplemental Digital Content 4 (http://links.lww.com/MSS/A174)). No correlation between RSR and regional T_{sk} was observed in males (Pearson r correlation: I1, 0.17 ± 0.23; I2, −0.11 ± 0.19).

DISCUSSION

The present study aimed to produce a whole body sweat map of aerobically trained white females at two exercise intensities in a temperate environment. A secondary aim of the study was to compare these data with whole body sweat maps of aerobically trained white males tested under the same experimental conditions (39). The data have clearly illustrated significant intra- and interregional variation in sweat rate in aerobically trained females, similar to that observed in males, and have shown large variation in absolute sweat rates between individuals. Regardless of the variation in absolute quantities of sweat produced, differences in distribution were observed between sexes, despite similarities in high and low sweat regions. Such differences should be considered in sex-specific application of clothing design, clothing evaluation with thermal manikins, and thermal modeling.

It is clear from the present data that absolute gross sweat rates were significantly higher in males compared with females exercising at the same relative work rate and unmatched for physical characteristics. This approach elicited a greater metabolic heat production in males (18) because of a higher absolute work rate compared with females and a greater body mass. This is largely reflected in the absolute regional sweat data in which 28 of the 34 regions measured were significantly higher in males than females at I1 and 32 of the 34 regions at I2. When considering distribution, at both exercise intensities, the males had a significantly higher distribution of sweat toward the torso, whereas the females had a significantly higher distribution toward the hands and feet in comparison with males. Comparing absolute sweat rates between sexes when exercising at similar rates of metabolic heat production (male I1 vs female I2), still, 17 of the 34 regions measured were significantly higher in males, mostly on the torso and legs, despite the similarity in GSL. Although the distribution of sweat was approximately similar between sexes, females did show a significantly higher distribution toward the arms (anterior and posterior) and hands (fingers, thumbs and dorsal hand) than the males, compared with a small number of regions showing a higher distribution of sweat on the torso in males compared with females. These data are consistent with previous UB sweat mapping data produced by our laboratory using males and females of equal aerobic fitness (22). These data observed no overall effect of sex but a significant zone and sex interaction, which showed that certain regions sweated more in males, whereas other regions sweated more in females. Similarly to the present data, the highest normalized sweat rates were observed on the midcentral back in both sexes (with exception only to the area between the breasts in females), sweating to be greater on the posterior compared with anterior torso, and lowest on the extremities.

Explaining the observed differences in sweat distribution both within and between sexes requires further investigation. They cannot be explained by T_{sk} in the present data, and high versus low heat-activated sweat gland distributions are reported to be similar in both males and females (28). Despite a higher heat-activated sweat gland density in females, there are no differences in total numbers of glands between sexes because of a greater surface area in males. Notably, a lower output per gland in females for a given thermal or pharmacological stimulus (5,25,34) may help explain the lower absolute RSRs in females compared with males, although not the regional differences, nor the effect on the heat balance this may have. In both sexes, regional sweat gland densities vary considerably over the body, with the greatest densities (glands per square centimeter) reported on the soles (620 ± 120), forehead (360 ± 60), and cheeks (320 ± 60), compared with the lowest values on the back, buttocks, arms, and legs

(ranging from 160 ± 30 to 120 ± 10, respectively) (42). Notably, these data used a small cadaver sample in which the type of sweat gland and its status as active or inactive was not discernible. A comprehensive review of torso sweat gland densities (inactive and active) is available from Machado-Moreira et al. (32), providing more reliable values. Regional glandular densities on the torso were relatively uniform (range: 115–81 glands per square centimeter on the abdomen and the chest and abdomen (umbilicus), respectively), failing to explain the regional sweating variation observed in the present study. Alternative explanations include the number of active sweat glands, output per gland, and sudomotor sensitivity. Segmental sudomotor sensitivity calculated by Machado-Moreira et al. (32) closely matched RSR variation observed in the current data, supporting this factor as a likely explanation.

Applications

Applications for the current data can be found in some areas. First, in models of human thermophysiology, these have moved over the last five decades from relatively simple two-node models (a core and a skin compartment) (16) to highly detailed multinode models that represent the whole body shape and calculate heat exchanges separately for many individual compartments (e.g., 63 body surface segments for Fiala et al. [11]). This means that heat transfer is calculated differently for a chest section than for an arm section, for example. Until the current data were available, this difference was only in the heat transfer coefficients (difference in movements), but now, also different sweat production levels for different areas can be included (11), providing an additional level of realism. The second application area is in clothing design. The body mapping data provided from the present and earlier work (12,39) have been used by sportswear designers to target areas of high sweat generation with additional ventilation openings and with fabrics with different absorption and wicking properties, thereby improving heat loss (38). Third, the obtained data feed directly into the design of sweating thermal manikins, used for the evaluation of clothing and environments; being able to provide a more realistic sweat distribution adds an extra level of realism.

CONCLUSION

During exercise in a temperate environment, aerobically trained white females demonstrated large regional variation in absolute RSR over the body but a consistent pattern of distribution. When compared with aerobically trained white males working at the same relative work rates, males showed a greater GSL compared with females, owing to a greater metabolic heat production. Despite this, males and females showed similar "high" and "low" sweat distributions; however, slightly different overall patterns of distribution were present between sexes. Males had a relatively higher distribution of sweat toward the torso compared with females, where the arms, hands, and feet contributed relatively more to total sweat loss in the females. Regional variation in sweat rate cannot be explained by regional skin temperature in the present study and does not correspond with regional sweat gland densities reported in the literature.

Limitations and Future Research

The present research has provided novel regional sweating data in white females and a comparison with white males under the same experimental conditions. It is difficult to dissociate the contributions of physical characteristics to the core temperature responses, requiring further studies using groups matched for physical characteristics to elucidate sex differences. Because of the applied and largely descriptive approach of this work, it is beyond the scope of the article to explain both the regional sweating variation and sex differences from a mechanistic viewpoint. Future work is needed to investigate regional differences in active eccrine sweat gland densities, gland sensitivity, and sudomotor innervation.

The authors acknowledge the continued support from the Adidas Innovation Team during this study, with special thanks to Berthold Krabbe, Brady Anderson, Jean Piere Roy, and James Lamont. The research presented was cofunded by the Adidas Innovation Team, Germany, and the Environmental Ergonomics Research Center, Loughborough University.

The authors are fully responsible for conducting the trial and for the data.

The authors declare that there are no conflicts of interest.

The results from the present study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES

1. American College of Sports Medicine. *ACSM's Guidelines for Exercise Testing and Prescription*. 6th ed. Baltimore (MD): Lippincott Williams & Wilkins; 2000. p. 72–7.
2. Avellini BA, Kamon E, Krajewski JT. Physiological responses of physically fit men and women to acclimation to humid heat. *J Appl Physiol*. 1980;49(2):254–61.
3. Avellini BA, Shapiro Y, Pandolf KB, Pimental NA, Goldman RF. Physiological responses of men and women to prolonged dry heat exposure. *Aviat Space Environ Med*. 1980;51(10):1081–5.
4. Bar-Or O. Effects of age and gender on sweating pattern during exercise. *Int J Sports Med*. 1998;19(suppl 2):S106–7.
5. Bar-Or O, Magnusson LI, Buskirk ER. Distribution of heat-activated sweat glands in obese and lean men and women. *Hum Biol*. 1968;40(2):235–48.
6. Bender R, Lange S. Multiple test procedures other than Bonferroni's deserve wider use. *BMJ*. 1999;318(7183):600–1.
7. Bittel J, Henane R. Comparison of thermal exchanges in men and women under neutral and hot conditions. *J Physiol*. 1975;250(3):475–89.
8. Buono MJ, White CS, Connolly KP. Cholinergic sensitivity of the eccrine sweat gland in trained and untrained men. *J Dermatol Sci*. 1992;4(1):33–7.

9. Dubois D, Dubois E. A formula to estimate the approximate surface area if height and weight be known. *Arch Intern Med*. 1916;17: 831–6.
10. Epstein Y, Stroschein LA, Pandolf KB. Predicting metabolic costs of running with and without backpack loads. *Eur J Appl Physiol*. 1987;56(5):495–500.
11. Fiala D, Havenith G, Brode P, Kampmann B, Jendritzky G. UTCI-Fiala multi-node model of human heat transfer and temperature regulation. *Int J Biometeorol*. 2012;56(3):429–41.
12. Fogarty AL, Barlett R, Ventenat V, Havenith G. Regional foot sweat rates during a 65-minute uphill walk with a backpack. In:Mekjavic IB, Kounalakis SN, and Taylor NAS, Eds. *Proceedings of the Environmental Ergonomics XII*; Ljubljana (Slovenia): Biomed d.o.o; 2007. p. 266–9.
13. Fox RH, Lofstedt BE, Woodward PM, Eriksson E, Werkstrom B. Comparison of thermoregulatory function in men and women. *J Appl Physiol*. 1969;26(4):444–53.
14. Frye AJ, Kamon E. Responses to dry heat of men and women with similar aerobic capacities. *J Appl Physiol*. 1981;50(1):65–70.
15. Frye AJ, Kamon E. Sweating efficiency in acclimated men and women exercising in humid and dry heat. *J Appl Physiol*. 1983;54(4): 972–7.
16. Gagge AP, Stolwijk JAJ, Nishi Y. An effective temperature scale based on a simple model of human physiological regulatory responses. *ASHRAE Trans*. 1971;77:247–62.
17. Gagnon D, Dorman LE, Jay O, Hardcastle S, Kenny GP. Core temperature differences between males and females during intermittent exercise: physical considerations. *Eur J Appl Physiol*. 2009;105(3):453–61.
18. Gagnon D, Jay O, Lemire B, Kenny G. Sex-related differences in evaporative heat loss: the importance of metabolic heat production. *Eur J Appl Physiol*. 2008;104(5):821–9.
19. Gagnon D, Kenny GP. Sex modulates whole-body sudomotor thermosensitivity during exercise. *J Physiol*. 2011;589(24):6205–17.
20. Grucza R, Lecroart J, Hauser J, Houdas Y. Dynamics of sweating in men and women during passive heating. *Eur J Appl Physiol Occup Physiol*. 1985;54(3):309–14.
21. Havenith G. Human surface to mass ratio and body core temperature in exercise heat stress—a concept revisited. *J Therm Biol*. 2001;26(4–5):387–93.
22. Havenith G, Fogarty A, Bartlett R, Smith CJ, Ventenat V. Male and female upper body sweat distribution during running measured with technical absorbents. *Eur J Appl Physiol*. 2008;104(2):245–55.
23. Havenith G, Luttikholt VG, Vrijkotte TG. The relative influence of body characteristics on humid heat stress response. *Eur J Appl Physiol Occup Physiol*. 1995;70(3):270–9.
24. Havenith G, Van Middendorp H. The relative importance of physical fitness, acclimatization state, anthropometric measures and gender on individual reactions to heat stress. *Eur J Appl Physiol*. 1990;61:419–27.
25. Inoue Y, Tanaka Y, Omori K, Kuwahara T, Ogura Y, Ueda H. Sex- and menstrual cycle–related differences in sweating and cutaneous blood flow in response to passive heat exposure. *Eur J Appl Physiol*. 2005;94(3):323–32.
26. Jackson AS, Pollock ML, Ward A. Generalized equations for predicting body density of women. *Med Sci Sports Exerc*. 1980;12(3): 175–81.
27. Kerslake D. *The Stress of Hot Environments*. Cambridge: Cambridge University Press; 1972. p. 121.
28. Knip AS. Measurement and regional distribution of functioning eccrime sweat glands in male and female caucasians. *Hum Biol*. 1969;41(3):380–7.
29. Kuno Y. *Human Perspiration*. Springfield: Charles C. Thomas Publ.; 1956. p. 190–204.
30. Livingstone SD, Nolan RW, Cain JB, Keefe AA. Effects of working in hot environments on respiratory air temperature. *Eur J Physiol Occup Physiol*. 1994;69(2):98–101.
31. Machado-Moreira CA, Caldwell JN, Mekjavic IB, Taylor NA. Sweat secretion from palmar and dorsal surfaces of the hands during passive and active heating. *Aviat Space Environ Med*. 2008;79(11):1034–40.
32. Machado-Moreira CA, Smith FM, van den Heuvel AM, Mekjavic IB, Taylor NA. Sweat secretion from the torso during passively-induced and exercise-related hyperthermia. *Eur J Appl Physiol*. 2008;104(2): 265–70.
33. Machado-Moreira CA, Wilmink F, Meijer A, Mekjavic IB, Taylor NA. Local differences in sweat secretion from the head during rest and exercise in the heat. *Eur J Appl Physiol*. 2008;104(2):257–64.
34. Madeira LG, da Fonseca MA, Fonseca IA, et al. Sex-related differences in sweat gland cholinergic sensitivity exist irrespective of differences in aerobic capacity. *Eur J Appl Physiol*. 2010;109(1): 93–100.
35. Parsons K. *Human Thermal Environments: the Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort and Performance*. 2nd ed. London: Taylor & Francis; 2003. p. 135.
36. Perneger TV. What's wrong with Bonferroni adjustments. *BMJ*. 1998;316:1236–8.
37. Shapiro Y, Pandolf KB, Avellini BA, Pimental NA, Goldman RF. Physiological responses of men and women to humid and dry heat. *J Appl Physiol*. 1980;49(1):1–8.
38. Shapiro Y, Pandolf KB, Goldman RF. Sex differences in acclimation to a hot-dry environment. *Ergonomics*. 1980;23(7):635–42.
39. Smith CJ, Havenith G. Body mapping of sweating patterns in male athletes in mild exercise-induced hyperthermia. *Eur J Appl Physiol*. 2011;111(7):1391–404.
40. Smith CJ, Machado-Moreira CA, Plant G, Hodder S, Havenith G, Taylor NAS. Design data for footwear - Sweating distribution on the human foot. *Int J Clothing Sci Tech*. In Press.
41. Smith CJ, Ventenat V, Havenith G. Regional sweat rates of the arms and hands in male squash players. In: Mekjavic IB, Kounalakis SN, and Taylor NAS, Eds. *Proceedings of the Environmental Ergonomics XII*. Ljubljana, Slovenia: Biomed d.o.o; 2007. p. 285–8.
42. Szabo G. The number of eccrine sweat glands in human skin. In: Montagna W, Ellis RA, Silver AF, editors. *Advances in Biology of the Skin*. London: Pergamon Press; 1962. p. 1–5.
43. Taylor NAS, Caldwell FN, Mekjavic IB. The sweating foot: local differences in sweat secretion during exercise-induced hyperthermia. *Aviat Space Environ Med*. 2006;77(10):1020–7.